AIRS Cryocooler System Design and Development

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ABSTRACT

JPL's Atmospheric Infrared Sounder (AIRS) instrument is based on a cryogenically cooled infrared spectrometer that uses a pair of pulse tube cryocoolers operating at 55 K to cool the HgCdTe focal plane to 58 K; the instrument also includes cryoradiators at 150 K and 190 K to cool the overall optical bench to 150 K. The cryocooler system design is a key part of the instrument development and focuses heavily on integrating the cryocoolers so as to maximize the performance of the overall instrument.

The cryocooler system development activity is a highly collaborative effort involving development contracts with industry and extensive cryocooler characterization testing at JPL. In the first phases of the effort, the overall cryocooler integration approach was developed by Lockheed Martin, and TRW was selected to develop and produce the flight coolers. The selected state-of-the-art pulse tube cooler has excellent thermal performance, and has a number of attributes—particularly light weight—that greatly improve instrument integration.

This paper describes the AIRS instrument overall cryogenic system design and the results achieved to date with respect to integration of the TRW pulse tube cryocoolers into this demanding instrument. Results are presented detailing the cryogenic loads on the cooler, the overall cryocooler thermal performance margins achieved, and thermal heatsinking considerations. Mass properties of the cryocooler system, and thermal properties of the developed cold link assembly are also presented.

INTRODUCTION

Instrument Overview

The objective of the Atmospheric Infrared Sounder (AIRS) instrument is to make precision measurements of atmospheric air temperature over the surface of the Earth as a function of height above the Earth's surface. The technical foundation of the instrument is a cryogenically cooled

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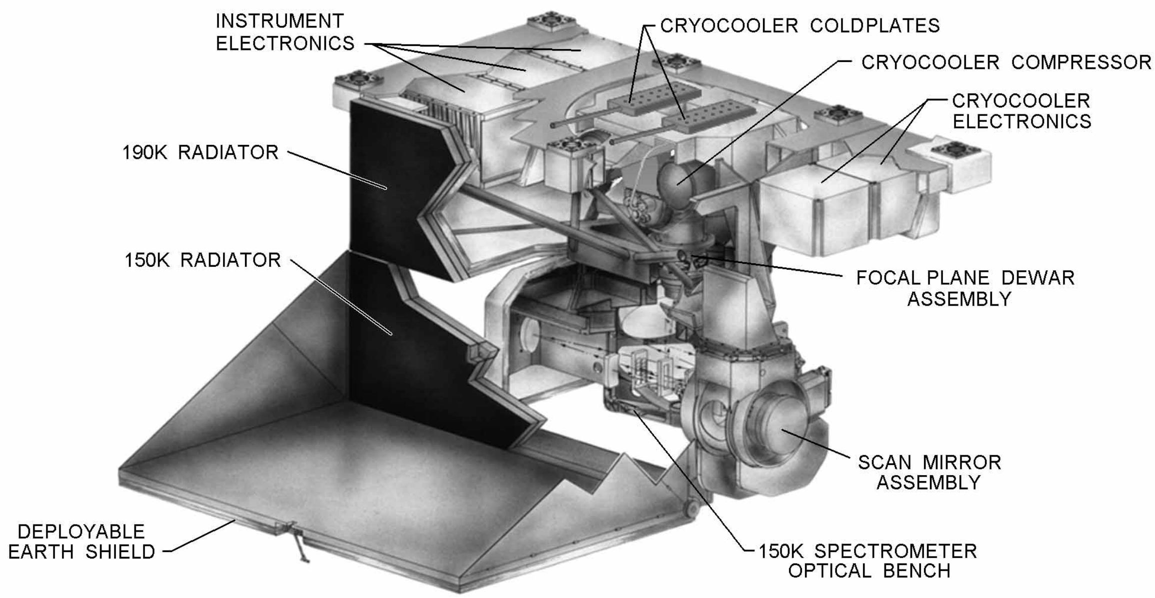

infrared spectrometer that uses a pair of 55K cryocoolers to cool the HgCdTe focal plane to 58 K; the instrument also includes a 150K-190K two-stage cryogenic radiator to cool the optical bench assembly to 150 K. The spectrometer operates over a wavelength range from visible through 15.4 µm, and places particularly demanding requirements on the thermal and vibration performance of the cryocooler.

The AIRS instrument is scheduled to be flown on NASA's Earth Observing System PM platform in the year 2000, and is being designed and fabricated under JPL contract by Lockheed Martin IR Imaging Systems (formerly Loral LIRIS) of Lexington, MA; it is in the detail design and flight hardware buildup phase at this time.

Figure 1 illustrates the overall instrument and highlights the key assemblies. Physically, the instrument is approximately 1.4 m x 1.0 m x 0.8 m in size, with a mass of 150 kg and an input power of 220 watts. Configurationally, the 58K IR focal plane assembly is mounted integrally with the 150K optical bench, which is in-turn shielded from the ambient portion of the instrument by a 190K thermal radiation shield and MLI blankets. The ambient portion of the instrument contains the high power dissipation components including the instrument electronics and the cryocoolers. These power-dissipating components have their heat rejection interface to a set of coldplates that conduct the heat to spacecraft-mounted radiators via a system of heatpipes.

Paper Organization

The remainder of the paper describes the details of the AIRS instrument cryogenic requirements and the approach used in the design of the cryosystem. This includes a detailed discussion of the cryocooler integration approach, performance predictions, and lessons learned to date with respect to the design and integration of the cryocoolers into the AIRS instrument.

AIRS INSTRUMENT CRYOGENIC DESIGN AND REQUIREMENTS

AIRS Cryosystem Conceptual Design

Early in the design of the AIRS instrument, key decisions of design philosophy were established that served as fundamental ground rules for the cryocooler system design. These included:

- Totally redundant cryocoolers—to avoid one cooler being a single-point failure
- No heat switches—to avoid increased complexity, cost and unreliability
- Ambient heat rejection to spacecraft-supplied cold plates operating between 10 and 25°C

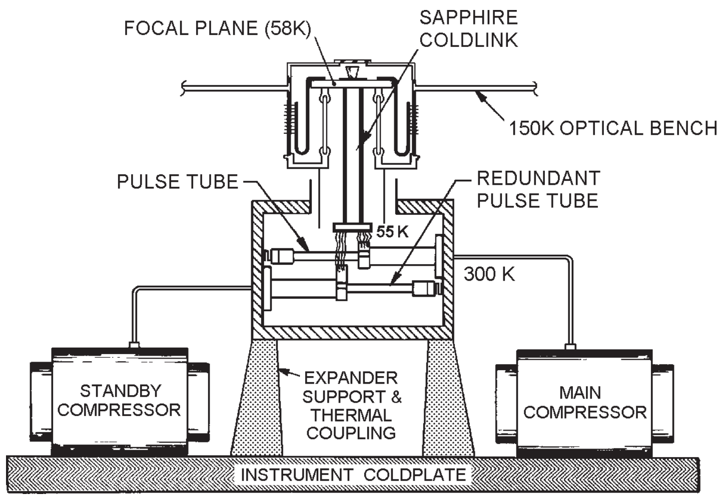

Figure 2. AIRS cryosystem conceptual design

- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics—to minimize asynchronous vibration or EMI noise pickup from the cryocooler
- Cold-end load (focal plane) mechanically mounted and aligned to the 150 K optical bench with a maximum vibration jitter on the order of 0.2 μm
- Focal plane calibration (for temperature, motion, etc.) every 2.67 sec (every Earth scan)
- Cooler input power goal of 100 watts (22 to 35 volts dc), and mass goal of 35 kg
- Cooler drive electronics fully isolated (dc-dc) from input power bus; EMI consistent with MIL STD 461

Based on the above fundamental ground rules, the AIRS cryosystem conceptual design, shown in Fig. 2, was developed. This system incorporates two independent 55K cryocoolers, a primary and a non-operating backup, each connected to the 58K focal plane using a common high-conductance coldlink assembly. Ambient heat from the operating cooler is rejected to the coldplates located in the plane of the instrument/spacecraft interface. Table 1 provides a breakdown of the approximate overall cryocooler refrigeration load for the AIRS instrument based on both the expected beginning-of-life (BOL) and possible end-of-life (EOL) properties of the cryosystem elements. A key determiner of these BOL/EOL loads is the temperature of the optical bench—assumed to be 145 K at BOL, and 160 K at EOL.

Cooler Sizing Calculations

In order to provide an accurate understanding of both the beginning-of-life (BOL) and end-of-life (EOL) cryocooler system performance, a sensitivity analysis of the cryocooler/load sys-

Table 1. Breakdown of AIRS cryocooler loads at 58 K

ITEM	Load (mW) BOL	Load (mW) EOL
Focal plane radiation load	70	100
Focal plane electrical dissipation	190	190
Conduction down wires and cables	100	120
Focal plane structural support conduction	130	160
Pulse tube snubber conduction	40	50
Radiation to coldlink assembly	90	120
Off-state conduction of redundant cryocooler	450	530
Total cryocooler load	1070	1270

Table 2. AIRS BOL/EOL performance margin analysis

PARAMETER	Unit	BOL Performance	200 mW Load Increase	15ºC Heatsink Increase	Cooler Wearout Degrad.	EOL Performance
Focal plane Temperature	K	58	58	58	58	58
Total Cooler Cold-End Load	W	1.07	1.27	1.07	1.07	1.27
Cooler Cold-tip ΔT to FP	K	3	3.4	3	3	3.4
Cooler Cold-tip Temperature (T_C)	K	55	54.6	55	55	54.6
Heat Rejection Coldplate Temp	K	290	290	305	290	305
Expander to Coldplate ΔT	K	11	13	13	15	23
Compressor to Coldplate ΔT	K	5	7	7	8	11
Avg. Cooler Rejection Temp (T_R)	K	298	300	315	301	322
T_C Correction for $T_R \neq 300$ K	K	+0.3	0	-2.5	-0.2	-3.7
T_C Correction for Cooler Wearout	K	0	0	0	-5.0	-5.0
Total Cold-tip Temp Correction	K	+0.3	0	-2.5	-5.2	-8.7
Effective 300K Cold-tip Temp (T_{EC})	K	55.3	54.6	52.5	49.8	45.9
Cooler Specific Power at T_{EC}	W/W	57	55	62	72	83
Cooler Compressor Power (P)	W	61	70	66	75	105
Total Input Power (P/0.89 + 12)	W	81	90	86	96	130
Compressor Stroke	%	64	68	67	70	80

tem has been conducted and periodically updated using BOL and EOL estimates of the key governing parameters. This analysis is summarized in Table 2. In this table, the column labeled "BOL Performance" presents the predicted performance for the 1070 mW nominal BOL cryogenic load noted in Table 1, together with BOL estimates of the cryocooler heat rejection temperature, and the baseline BOL performance of the cryocooler (presented in Fig. 3 for 300 K heat rejection temperature). For heat rejection temperatures different from 300 K, the cold-tip temperature for a given load and input power rises approximately 1 K for each 6 K increase in heat rejection temperature. Note that this correction is included in the line "T_C Correction for $T_R \neq 300$ K."

The middle three columns of Table 2 predict the performance of the AIRS cooler with the

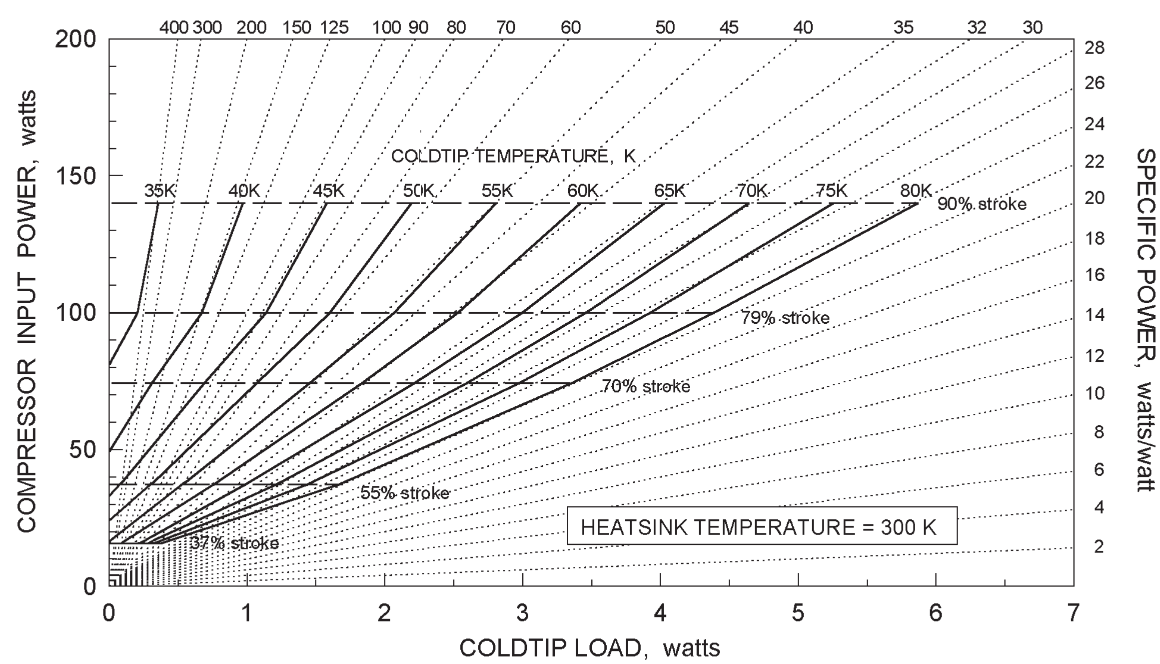

Figure 3. Baseline thermal performance of the AIRS pulse tube cooler with 300 K heat rejection temperature

individual EOL effects of a 200 mW increase in the cryocooler load (as noted in Table 1), a 15°C increase in the cryocooler heat rejection temperature, and a nominal value for EOL cryocooler degradation, respectively. End-of-life performance of the cryocooler is modeled as a 5K shift in the cryocooler load line, i.e. the EOL input power at 55 K is the same as the BOL input power at 50 K for the same cryogenic load. Based on lifetest experience to date, this 5 K degradation of performance at EOL appears to be a conservative, yet reasonable assumption.

The right most column of Table 2 represents the computed EOL performance of the AIRS cryocooler system. Note that the predicted difference between EOL and BOL performance is very significant — nearly a factor of two in compressor input power. Table 2 demonstrates the good match of the AIRS cooler to the requirements of the AIRS instrument over its total life cycle, including representative end-of-life degradation. With the assumed end-of-life degradation, the cooler performance satisfies the focal plane cooling requirement and remains within the nominal operating range of the compressor, i.e. less than 80% of maximum stroke.

DEVELOPMENT WORK LEADING UP TO FLIGHT COOLER SELECTION

Because the required cryocooler performance, noted in Fig. 3, was greater that any existing cryocoolers at the beginning of the AIRS development effort, the AIRS Project established a collaborative in-house/contractor teaming approach to achieve the necessary cryocooler technology advances. This approach involved the establishment of an extensive cryocooler characterization program at JPL[1] to provide the foundation of cryocooler performance data needed, and a contractor-based effort lead by JPL's AIRS instrument systems contractor, Lockheed Martin IR Imaging Systems (formerly Loral LIRIS), to expand the performance of the first-generation coolers to meet the AIRS requirements. This contractual effort proved the feasibility of achieving the AIRS requirements, and fostered important design improvements associated with reduced off-state conduction down the cold finger, and high accuracy cold-tip temperature regulation via compressor piston stroke control.[2,3]

Following four years of extensive cryocooler characterization and development contracts, TRW was awarded the contract to develop and produce the flight coolers for the AIRS instrument. The selected state-of-the-art pulse tube cooler builds on the demonstrated performance of the successful TRW 1W-35K pulse tube cryocooler,[4,5] and promises excellent thermal performance, comparable to the best Stirling coolers; it also offers a number of features that greatly improve instrument integration, such as reduced mass, size and complexity, increased stiffness, and reduced vibration at the cold head.

FLIGHT CRYOCOOLER SYSTEM DETAIL DESIGN

Upon selection of the TRW pulse tube cooler and the AIRS cryosystem concept illustrated in Fig. 2, work was focused on developing the flight cooler and resolving the details of a number of key design-integration trade-offs.

Pulse tube Expander Integration Considerations

To minimize thermal conduction losses between the focal plane and the cryocooler, the pulse tube coldblock needs to be located close to the focal plane. Unfortunately, in addition to providing refrigeration, the expander of a modern high-efficiency Stirling or pulse tube refrigerator also dissipates a large amount of ambient heat — often 50% of the total compressor input power. Thus, the expander also needs to be mounted close to the instrument heat rejection system in order to minimize its operating temperature and maximize its efficiency. With the AIRS instrument, the distance between the focal plane and the instrument heat-dissipation cold plates is approximately 45 cm (18 inches). This distance has to be spanned by a combination of the cooler-focal plane coldlink assembly and the pulse tube expander heat-rejection mounts.

The AIRS pulse tube expander/coldlink integration design is illustrated in Fig. 4. This configuration uses high-cross-section aluminum structural members to heatsink the expanders to

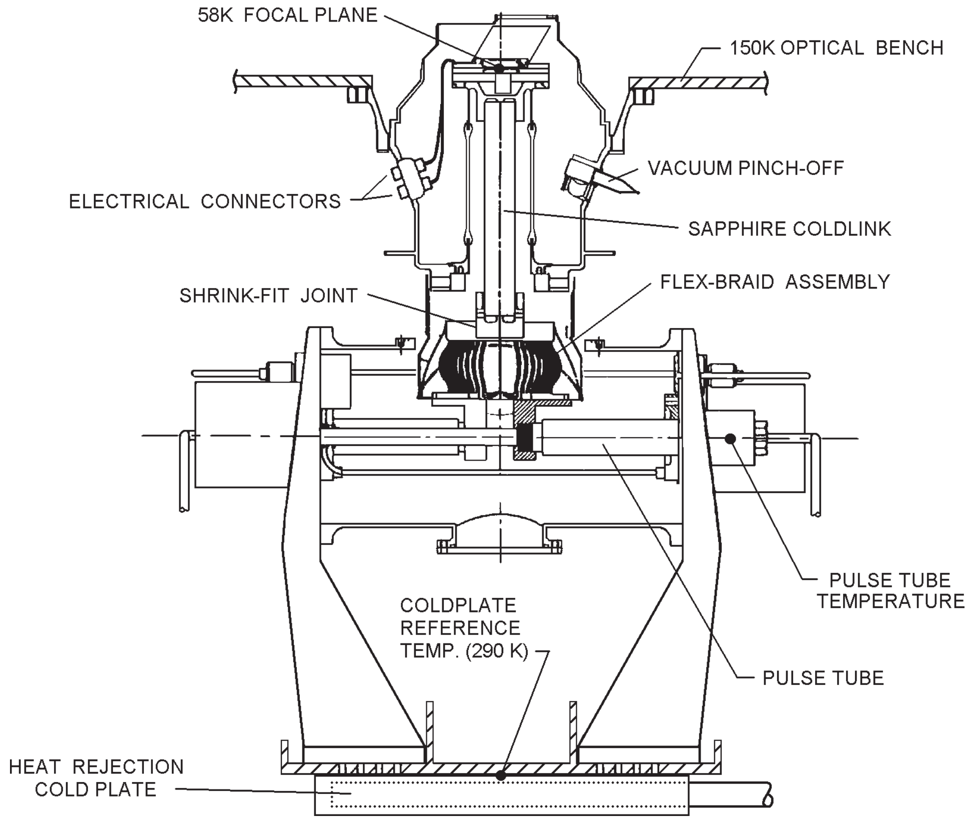

Figure 4. AIRS focal plane/cryocooler integration approach

the spacecraft coldplates, and a high-conductance Sapphire coldrod/flexlink assembly to connect the pulse tube coldblock to the instrument focal plane.

Sapphire Coldlink Assembly. As shown in Fig. 5, the sapphire coldlink assembly—designed and fabricated by Lockheed-Martin—contains a copper-braid flexlink section to accommodate the relative motion that occurs between the pulse tube and the focal plane dewar during launch and during cooldown of the instrument to cryogenic temperatures. The copper flexlink assembly bolts directly onto the two pulse tube coldblocks at one end, and at the other end attaches to the gold-plated sapphire coldrod using a molybdenum/aluminum shrink-fit interface.

Figure 5. AIRS focal plane/pulse tube coldlink assembly

Table 3. Breakdown of AIRS coldlink assembly thermal resistance

ITEM	Resistance (K/W)
Focal plane to Sapphire rod	1.57
Conduction down Sapphire rod	0.16
Sapphire rod to moly coupling	0.34
Resistance across shrink-fit joint	0.40
Resistance across flex braid	1.35
Coldblock contact resistance	0.30
Total focal plane/pulse tube thermal resistance	4.12

The total measured thermal resistance of the complete coldrod assembly from the pulse tube coldblock to the focal plane active elements is approximately 4K/W; the details of this resistance are shown in Table 3. In addition to the copper-braid section that connects the pulse tube coldblocks to the sapphire rod, the cold link assembly also contains copper braids that connect the coldblocks to one another so that the appreciable (~0.5 watt) off-state conduction of the redundant cryocooler pulse tube does not have to be conducted to the Sapphire rod and back to the operating cooler.

Pulse Tube Expander Aluminum Heatsinks. The pulse tube heatsink structural/thermal mount, also illustrated in Fig. 4, has been designed and fabricated by TRW as part of the structural support of the pulse tube/coldlink vacuum-housing assembly. This mount is required to conduct up to 40 watts from the operating expander to the cryocooler heat-rejection coldplate while simultaneously minimizing the rejection temperature of the pulse tube and the total required mass. The design achieves a thermal resistance of approximately 0.4 K/W from the pulse tube regenerator base to the 290 K coldplate interface.

Compressor Thermal-Structural Mounting Considerations

As with the expanders, minimizing the temperature of the compressors is equally important to achieving high cryocooler efficiency. This has been accomplished by mounting the AIRS compressors as close to the instrument heat-rejection coldplates as possible, yet also as close to the expanders as possible so as to minimize the length of the interconnecting transfer line. A second important consideration has been to uniformly spread the thermal dissipation over the surface of the coldplates so as not to create local high-heat-flux areas within the heatpipe evaporators that might lead to heatpipe dryout and depriming. The AIRS compressor mounting ap-

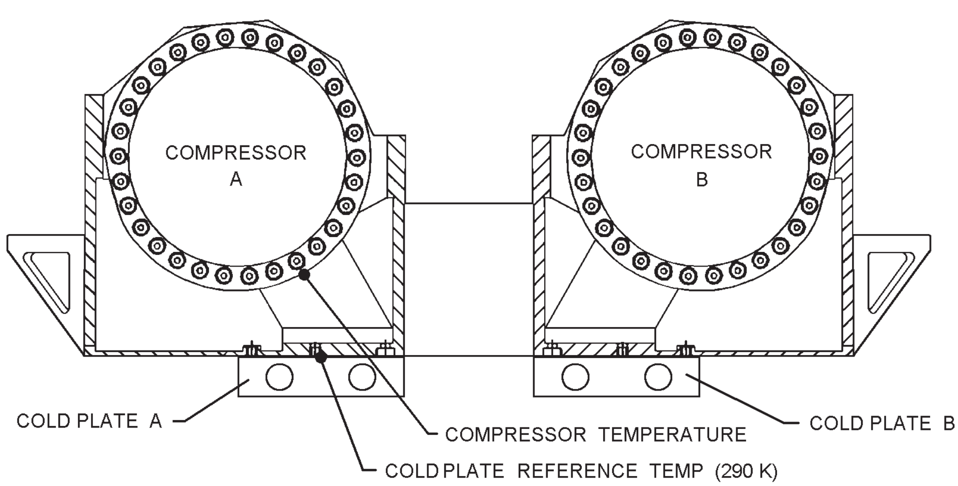

Figure 6. AIRS cryocooler compressor mounting approach and heat transfer interface

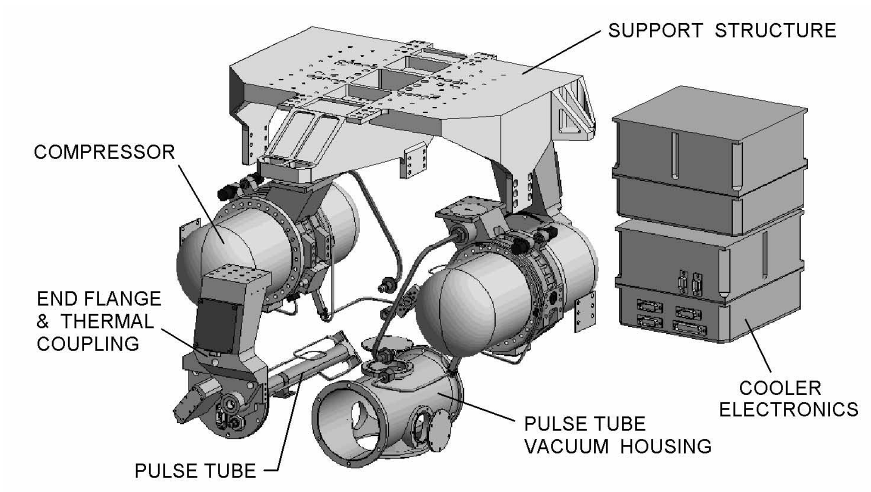

Figure 7. Exploded view of AIRS cryocooler assembly

proach, illustrated in Fig. 6, was a trade-off of mass against ΔT and resulted in a final thermal resistance of approximately 0.2 K/W between the compressor outer shell and the 290K coldplate reference temperature.

Cryocooler Electronics

In addition to the cryocooler thermal/mechanical components, the cooler drive electronics are a key part of the overall AIRS cryocooler system and play a critical role in the cooler integration. An exploded view of the total cryocooler assembly including the electronics is shown in Fig. 7. The cooler electronics not only drive the compressors with high electrical efficiency, but also perform a number of vital control, noise suppression, and data acquisition functions.[6] Key attributes of the AIRS cryocooler drive electronics include:

- Very high electrical efficiency (90% throughput to the compressors) including full (dc-dc) transformer isolation from input power bus (23 to 35 volts dc)
- Built-in shorting relays to suppress cooler piston motion during launch
- Cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics—to minimize asynchronous vibration or EMI noise pickup from the cryocooler
- Very high degrees of EMI shielding, consistent with MIL STD 461
- Advanced feedforward vibration suppression system with accelerometer-based closed-loop nulling of the first 16 cooler vibration harmonics
- Precision closed-loop cooler coldblock temperature control via piston stroke control
- Built-in monitoring of cooler operational variables and performance data
- Built-in low-frequency stiction test drive waveform

AIRS CRYOCOOLER DEVELOPMENT STATUS

In Spring 1994, TRW was awarded the contract to develop and produce the flight coolers for the AIRS instrument. Presently, the first flight-like engineering model (EM) cooler assembly has been completed, and was delivered to JPL for testing in May 1996. This cooler, shown in Fig. 8, has one flight-like compressor and associated pulse tube; to reduce cost, the second redundant cooler is a mass and thermal mock-up. This unit has been performance tested at TRW,[7] including full launch vibration qualification testing, and is presently undergoing additional characterization testing at JPL including EMI, off-state conduction, vibration modal testing, and coldblock temperature controller dynamic performance. The excellent mass properties of the AIRS cryocooler system are summarized in Table 4.

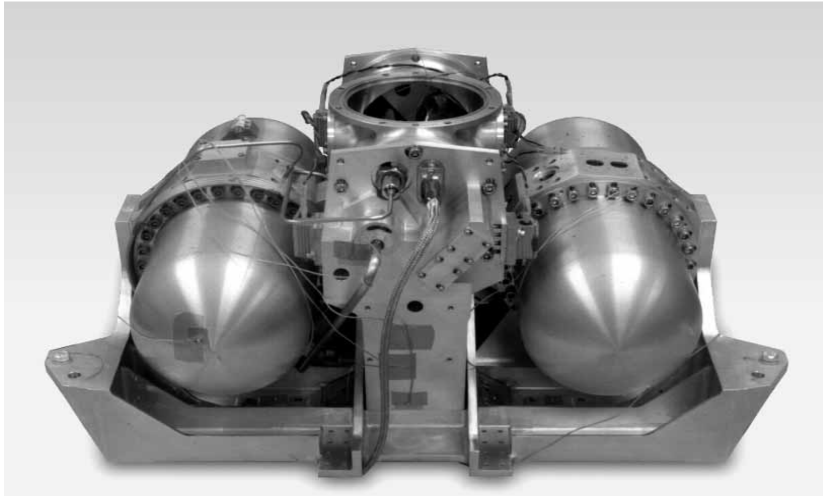

Figure 8. AIRS Engineering Model cryocooler assembly during testing at JPL

In addition to the AIRS EM cooler, TRW has completed a pair of similar pulse tube cryocoolers for the Air Force/BMDO.[8] These AIRS-like pulse tube coolers have been extensively characterized at JPL over the past year under joint AIRS/Air Force sponsorship and have led to a wealth of performance data generally applicable to the AIRS cooler design.[9]

Upon completion of the characterization testing at JPL, the AIRS EM cooler will be delivered to Lockheed Martin IR Imaging Systems in Lexington, MA, in summer 1996. There, it will start an extensive series of integration tests with the Lockheed-Martin coldlink/focal plane assembly and the complete Engineering Model AIRS instrument. The AIRS flight (PFM) coolers are scheduled for completion of full qualification testing and delivery to Lockheed Martin around the beginning of calendar 1997.

SUMMARY AND CONCLUSIONS

The AIRS cryocooler system development activity is a key part of the AIRS instrument development and focuses on developing and integrating the cryocoolers so as to maximize the performance of the overall instrument; it is a highly collaborative effort involving development contracts with Lockheed Martin and TRW, and cryocooler characterization testing at JPL. To date, the overall cryocooler integration approach has been developed and refined, and the state-of-the-art TRW pulse tube cooler has demonstrated excellent thermal performance and light weight.

Table 4. Breakdown of mass of AIRS cryocooler assembly

ITEM		Mass (kg)
Total cryocooler A (primary) weight		12.5
Compressor A	8.4	
Pulse tube expander A	0.3	
Electronics A	3.8	
Total cryocooler B (backup) weight		12.5
Pulse tube vacuum housing and heat sinks		3.8
Integrating structure/coldplate support		5.2
Compressor-to-electronics cables (2 sets)		1.0
Total cryocooler assembly		35.0

Results have been presented detailing the cryogenic loads on the cooler, the overall cryocooler thermal performance margins achieved, and thermal heatsinking considerations. Mass properties of the cryocooler system, and thermal properties of the developed coldlink assembly have also been presented.

ACKNOWLEDGMENT

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